SAND2021-14511R

I Electric Drive Technologies

I.1 Electric Drive Technologies Research

I.1.1 Component Modeling, Co-Optimization, and Trade-Space Evaluation (Sandia National Laboratories)

Jason Neely, Principal Investigator
Sandia National Laboratories
P.O. Box 5800, MS 1152
Albuquerque, NM 87185
E-mail: jneely@sandia.gov

Susan Rogers, DOE Technology Development Manager
U.S. Department of Energy
E-mail: susan.rogers@ee.doe.gov

Start Date October 1, 2018: End Date: September 30, 2023
Project Funding (FY21): $300,000 DOE share: $300,000 Non-DOE share: 0

Project Introduction

This project is intended to support the development of new traction drive systems that meet the targets of 100 kW/L for power electronics and 50 kW/L for electric machines with reliable operation to 300,000 miles. To meet these goals, new designs must be identified that make use of state-of-the-art and next-generation electronic materials and design methods. Designs must exploit synergies between components, for example converters designed for high-frequency switching using wide band gap devices and ceramic capacitors. This project includes: (1) a survey of available technologies; (2) the development of design tools that consider the converter volume and performance; (3) exercising the design software to evaluate performance gaps and predict the impact of certain technologies and design approaches, i.e. GaN semiconductors, ceramic capacitors, and select topologies; and (4) building and testing hardware prototypes to validate models and concepts. Early instantiations of the design tools enable co-optimization of the power module and passive elements and provide some design guidance; later instantiations will enable the co-optimization of inverter and machine. Prototype testing begins with evaluation of simpler conversion topologies (i.e. the half-bridge boost converter) and progresses with fabrication of prototype inverter drives.

Objectives

For FY21, objectives included

- Investigate the feasibility of using nano-composite materials to realize a distributed EMI filter
- Investigate the use of 3D printed ceramics to improve thermal management
- Continue to Generate high-fidelity dimensional and electrical models for principal power electronic components within a novel inverter design
- Co-Optimize inverter design with machine model for power density, reliability, and efficiency
- Select a candidate inverter design from the Pareto-Optimal front, build, and test it

Approach

The R&D approach employed by the team includes four strategies for generating design guidance and optimal designs, listed in order of increased fidelity and resources:

1. ***Empirical and First-Principles Analysis***: This uses first-principles knowledge, such as physical models, as well as comparative designs to inform the design.

2. ***High-Fidelity Modeling and Analysis***: This uses higher-order models that consider the component equivalent circuits, dimensions, reliability calculations, etc.
3. ***Global Co-Optimization***: With the definition of one or more performance metrics, components are simulated together and their performance is measured and compared.
4. ***Hardware Iteration***: Using optimal designs identified in software, hardware exemplars are built and evaluated; 3 and 4 are iterated to create the best results.

In FY21, the project included elements of all four strategies, applied with different weight to the five objectives. Empirical analysis and modeling were applied to evaluate the feasibility of realizing a distributed filter using nanocomposite and to investigate the use of 3D printed ceramics for improving thermal management. Project efforts also continued to improve the fidelity of component models, developing the optimization software into a tool to identify designs in the Power Density-MTBF trade-space, using this software also to predict converter performance for SiC vs GaN and film vs ceramic capacitors, and building a power converter prototype to validate models. Hardware iteration also continued with inverter fabrication and test.

Based on the optimization results attained for an inverter drive in FY20, the principle contributors to inverter volume remained to be the thermal management components (i.e. the cold plate) and the AC EMI filter that connected the inverter drive to the motor. In particular, the optimization had selected for designs with 5 or more phases (i.e. multi-phase designs), ceramic capacitors, and higher-frequency switching. This primarily reduced the dc link capacitor size, but the greater number of phases increased the footprint of the devices and increased the number of EMI filter elements (i.e. more inductor cores). Thus, in FY21, the team investigated two approaches to mitigate filter and thermal management component size.

To address the filter size, the feasibility of using nano-composite materials to realize a distributed EMI filter was investigated. Specifically, the nanocomposite material, when evaluated as a bulk material, is insulating and has a magnetic permeability of $\mu_r \sim 5\text{-}10$; based on the spacing of nanoparticles and the permittivity of the epoxy, the material should have a permittivity of $\varepsilon_r \sim 5\text{-}10$. If the conductor spacing, geometry, and length are such that the distributed capacitance and inductance between conductors are sufficient, then EMI filtering can be accomplished in the AC bus (estimated to be approx. 10 cm long) if a nanocomposite encapsulant is used for the insulation. In FY21, the team investigated the feasibility of this approach using COMSOL multi-physics simulations.

To address the thermal management size, the team investigated the use of 3D printed ceramic components that could be used to realize a "surround cooling" capability that could be simpler and potentially more effective than double-sided cooling. In FY21, the team obtained samples of 3D printed material from Lithoz, performed flash diffusivity measurements to determine key parameters, and evaluated the efficacy of different geometries on managing heat using COMSOL Multi-physics simulations.

For the optimization work, the team continued to use the Genetic Optimization System Engineering Tool (GOSET) developed by Purdue University [1]. This MATLAB®-based software package consists of several scripts for implementing and solving a genetic algorithm optimization problem. The genetic algorithm is a probabilistic method for optimizing multi-input systems with non-convex solution spaces using the principles of genetics and a user-defined fitness function. GOSET allows for multiple fitness functions to be co-optimized into a Pareto front. To set up the optimization, the circuit schematic and physical layout were partially defined, and the dimensions of and between components, thicknesses of insulators, lengths of conductors, choice of SiC or GaN, number of phases, etc. were formulated and linked to the schematic definition in order to compute a volume and evaluate the circuit/system performance using a dynamic simulation. As described in the previous report, to evaluate system reliability, component mean time between failure (MTBF) quantities were also computed for SiC MOSFETS and capacitors using MIL-HDBK-217F calculations [2].

In FY21, the team worked to validate the simulation models used for optimization using test results from the boost converter built in FY20. The team also worked to increase the fidelity of component models developed for inductors, capacitors, switches, and heatsinks. Revised models were extended to the development of a 10 kW peak, 5.5kW continuous multi-phase inverter. A set of inverter designs in the power density-MTBF design space were identified using GOSET, and a candidate design was selected and built.

Results

Feasibility Study of Distributed Filter

To investigate whether distributed inductance and capacitance might be sufficient to accomplish low-pass filtering and allow for the elimination of lumped-element inductors and capacitors, detailed COMSOL simulations were performed initially on a 2-conductor example. These assumed a 20 cm length, a flat rectangular copper conductor, and an insulating medium with $\mu_r = 10$ and $\varepsilon_r = 10$. Simulations were done on 2D and 3D cases. See illustration of 2D simulation results in Figure I.1.1.1 and illustration of 3D results in Figure I.1.1.2.

For this configuration, simulations identified potential for $L \sim 1.8$ µH/m and $C \sim 588$ pF/m. For these values and a candidate bus cable length of 20 cm, the cut-off frequency was estimated to be $f_c \sim 24.5$ MHz. This is well above the switching frequency of the converter (100s of kHz) and would thus be insufficient for filtering ripple. In addition, even for EMI filtering, if one were to assume a transition time of 100 nsec (T_{on} or T_{off}), one would need a filter cutoff well below 3.5 MHz. Thus, the team has concluded that this approach is not likely to work as proposed. The team will next consider the potential of using distributed inductance (to eliminate the inductor core) combined with lumped capacitor elements.

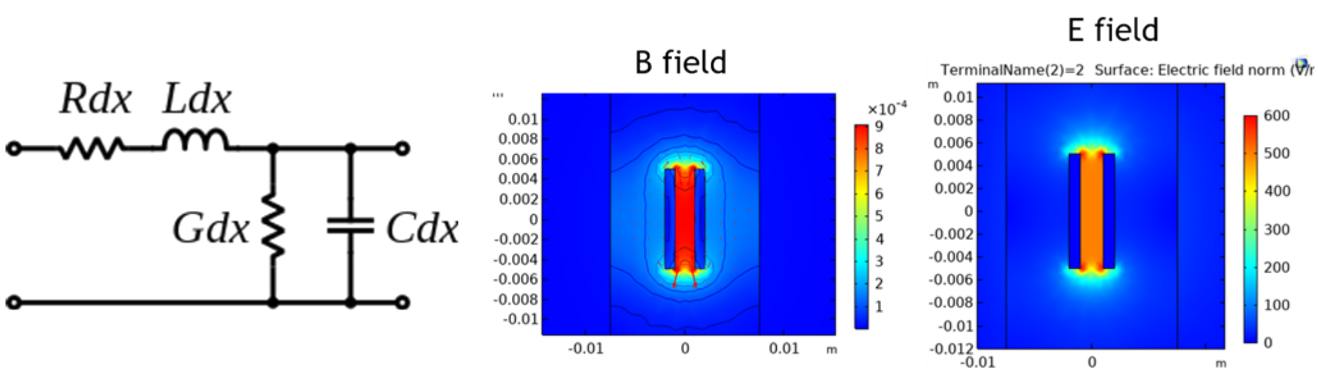

Figure I.1.1.1: (Left) Simplified Schematic of distributed inductance and capacitance (center) B-field simulations in COMSOL and (right) E-field simulations in COMSOL

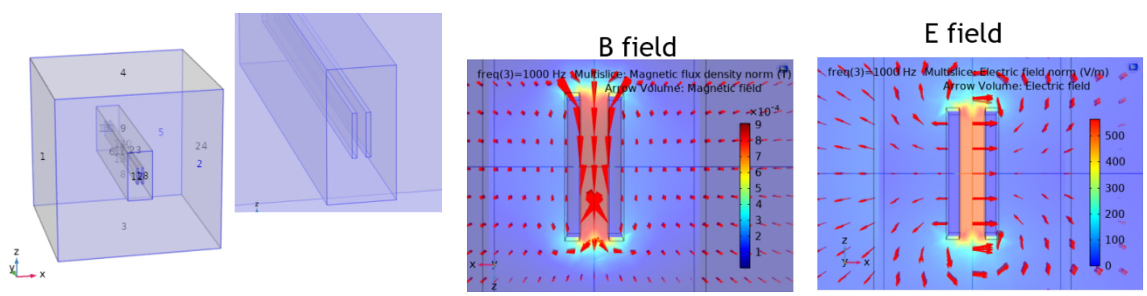

Figure I.1.1.2: (Left) 3D rendering of 2-conductor configuration (right) illustration of B-field and E-field lines in 3D

Investigation of 3D printed ceramics to improve thermal management

To improve thermal management, either to reduce the volume of thermal management components, or to reduce junction temperatures for a given volume, a new approach was investigated for the removing heat from the semiconductor devices. Specifically, 3D printed Al_2O_3 ceramic components can be used to surround and even encase electronic components with significant thermal loads. With this approach, a cold plate would still be used, but the ceramic components would route heat away from the top of devices down to the cold plate. This accomplishes double-sided cooling but avoids the complexity of contemporary assemblies. These components can have high resolution features ~100 µm and thus tightly fit around components and potentially include additional features, such as fins. To investigate this approach, samples were acquired from Lithoz and tested using flash diffusivity measurements. Printed Al_2O_3 ceramics measured thermal conductivities ranged from: 33.5 to 38.7 W/m-K and demonstrated a linear correlation with density. See Figure I.1.1.3.

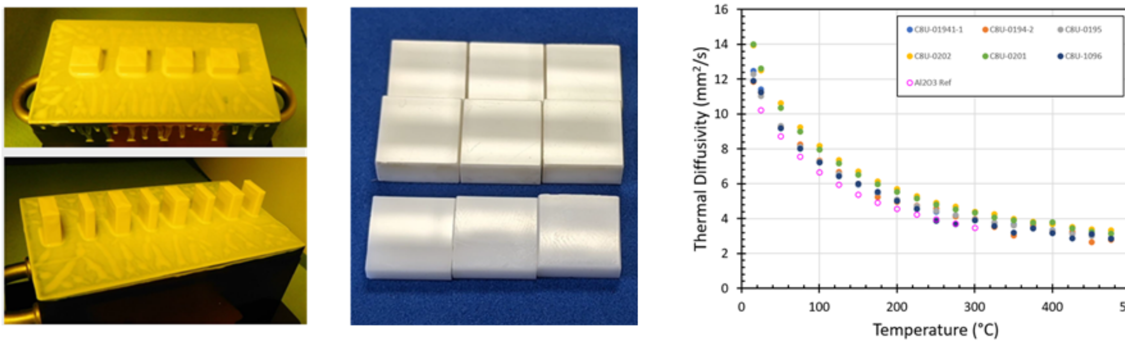

Figure I.1.1.3: (Left) As printed Al_2O_3 samples (center) sintered and polished samples and (right) measured thermal diffusivity as a function of temperature

These parameters were then used to inform COMSOL simulations to evaluate three design cases. Case 1 is the baseline case with a 2x2 mm die bonded to a substrate and dissipating 10 W. Case 2 adds a ceramic structure around the device and encapsulates with a thermal epoxy. Case 3 fully encases the device and adds fins to the topside to enhance cooling. This preliminary modeling study showed a potential 11% and 29% reduction in temperature rise for Case 2 and Case 3 respectively, compared to the baseline. See Figure I.1.1.4 for an illustration of the three cases and a plot of simulated temperature rises.

The results of this simulation study are very promising, and the team plans to continue this work in FY22, including the fabrication and test of candidate Al_2O_3 ceramic components.

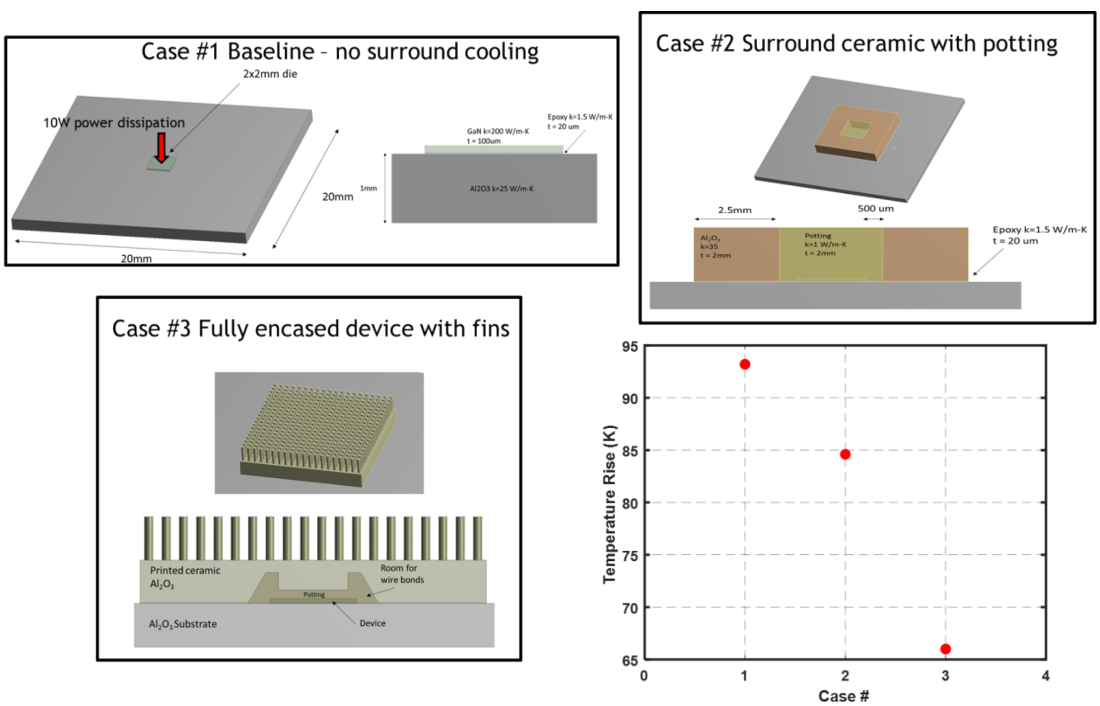

Figure I.1.1.4: Illustrates three design cases and the simulated temperature rise of the device junction for each

Optimization of Inverter Drive Volumetric Power Density, Efficiency, and MTBF

The team used GOSET to identify a set of designs for 10 kW peak, 5.5 kW continuous that were optimized in the efficiency-power density design space. This is an extension of the work in FY20 [3],[4]. A candidate design with 5 phases and a potential power density of 42.3 kW/L and 95.6% efficiency (at full voltage and steady-state power) was identified, and a prototype was designed. See Figure I.1.1.5. Therein, it is noted that the cold plate and AC filter inductors still dominate the size of the prototype. The prototype was built and tested. Thus far, the optimized inverter prototype has been tested up to 400 V with a demonstrated ~98% efficiency. Experimental voltage and current waveforms have also been validated against the simulation model at these voltage and power levels. The test setup, inverter photo and select waveforms are shown in Figure I.1.1.6. Evaluation of the prototype is ongoing.

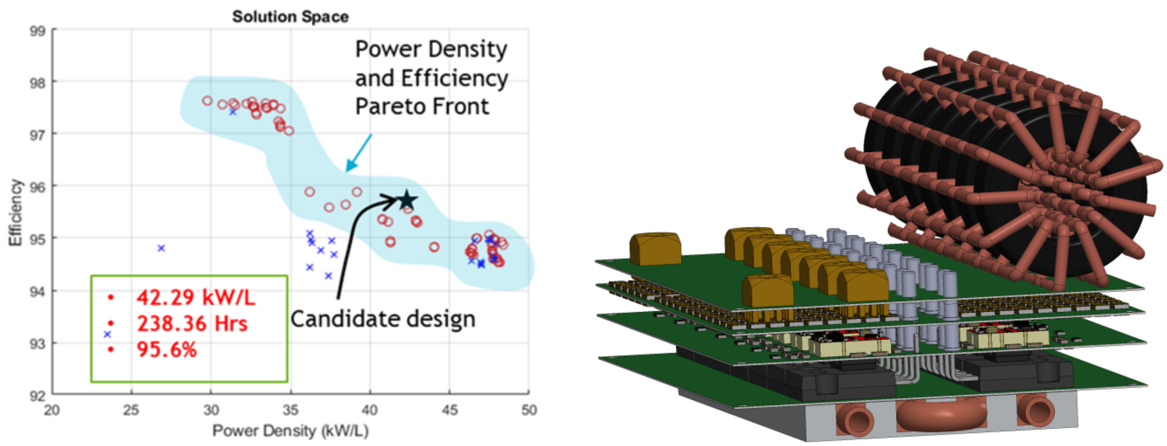

Figure I.1.1.5: (Left) Pareto Optimal Front with Candidate design indicated and (Right) 3D illustration of candidate design

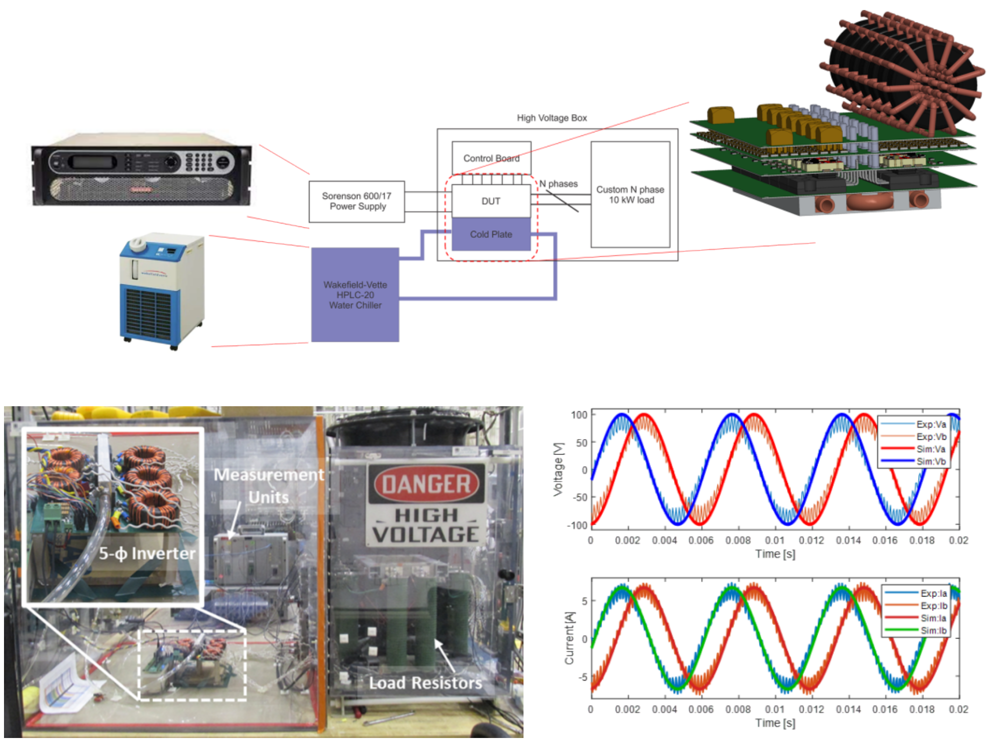

Figure I.1.1.6: (Top) Experimental setup (bottom Left) Prototype 5-phase Inverter in protective enclosure and (bottom right) simulated and measured waveforms

Finally, to support a more comprehensive optimization and prototype selection going forward, the optimization configuration was changed to enable co-optimization across three objectives: Power density, MTBF, and conversion Efficiency and to display the Pareto Optimal front as a surface. See Figure I.1.1.7. This approach is expected to better illustrate the tradespace and to provide better design choices going forward.

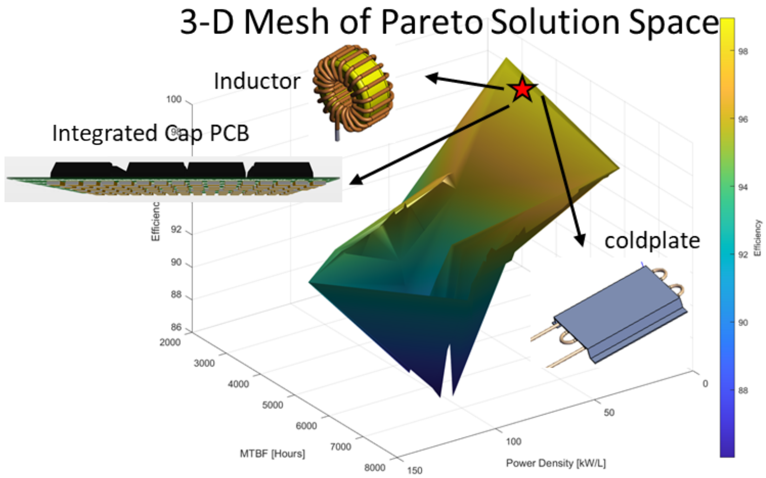

Figure I.1.1.7: 3D Pareto-Optimal Surface (3 objectives) for Power Density, MTBF, and Efficiency

Conclusions

This project is focused on developing improved designs for future traction drive systems through the combined use of WBG devices, ceramic capacitors, high-frequency switching, and multi-phase designs that enable considerable improvements in power density. Designs are developed with the help of tools developed to perform multi-objective optimizations on electric drive designs. Unlike previous work, these include optimizations that consider component reliability, herein computed as mean time between failure (MTBF). In FY21, the project team continued the development and use of an optimization tool based on GOSET [1] to co-optimize converter power density, efficiency, and mean time between failures (MTBF) in a 10 kW peak, 5.5 kW continuous multi-phase inverter. A pareto optimal front was first generated in the efficiency-power density design space, an inverter design was selected, built, and tested to validate time-domain performance predictions. The project team later modified the optimization software to co-optimize across three objectives that include efficiency, power density, and MTBF. The team also investigated new approaches to reduce the size of the AC filter using distributed inductance and capacitance, but this scheme seems unlikely to yield a large benefit. The team also investigated the use of 3D printed Al_2O_3 ceramic components to aid in thermal management; the results of this work are very promising. Future work will refine the design tools and extend their use to optimize the inverter designs across the three design objectives, and to co-optimize the inverter and machine designs. The team will also continue the investigation of 3D printed Al_2O_3 ceramic components for thermal management.

Key Publications / Presentations

1. J. Neely, G. Pickrell, J. Flicker, L. Rashkin, R. Kaplar, "The Case for Vertical Gallium Nitride Devices in Electric Vehicle Drives," *2020 IEEE Applied Power Electronics Conference* (APEC2020), Industry Session: Vehicle Electrification II.
2. L. Gill, J. C. Neely, L. J. Rashkin, J. D. Flicker and R. J. Kaplar, "Co-Optimization of Boost Converter Reliability and Volumetric Power Density Using Genetic Algorithm," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 5302-5309, doi: 10.1109/ECCE44975.2020.9235716.

3. L. Rashkin, J. Neely, L. Gill, J. Flicker and R. Darbali-Zamora, "Optimal Power Module Design for High Power Density Traction Drive System," *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, Chicago, IL, USA, 2020, pp. 134-138, doi: 10.1109/ITEC48692.2020.9161703.

References

[1] S. D. Sudhoff, GOSET: Genetic Optimization System Engineering Tool: For Use with MATLAB®, version 2.6, January 1, 2014.

[2] *Military Handbook: Reliability prediction of electronic equipment*, 1991. Available: https://snebulos.mit.edu/projects/reference/MIL-STD/MIL-HDBK-217F-Notice2.pdf

[3] L. Gill, J. C. Neely, L. J. Rashkin, J. D. Flicker and R. J. Kaplar, "Co-Optimization of Boost Converter Reliability and Volumetric Power Density Using Genetic Algorithm," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 5302-5309, doi: 10.1109/ECCE44975.2020.9235716.

[4] L. Rashkin, J. Neely, L. Gill, J. Flicker and R. Darbali-Zamora, "Optimal Power Module Design for High Power Density Traction Drive System," *2020 IEEE Transportation Electrification Conference & Expo (ITEC)*, Chicago, IL, USA, 2020, pp. 134-138, doi: 10.1109/ITEC48692.2020.9161703.

Acknowledgements

This work is supported by the DOE Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government.